Ex-1 **Shell and Tube Heat Exchanger**

A shell and tube heat exchanger is to be designed to sub-cool condensate from a methanol condenser from 95°C to 40°C. Flow-rate of methanol is 100,000 kg/h. Brackish water will be used as the coolant, with a temperature rise from 25° to 40°C. A pressure drop of 0.8 bar is permissible on both streams. Allowance should be made for fouling by including a fouling heat transfer coefficient for methanol as 5000 (W/m^2.°C) and 3000 (W/m^2.°C) on the brackish water stream. Thermal conductivity of cupro-nickel alloys is 50 W/m.°C.

The fluid properties at their mean temperatures are given as:

Property	Water (at 32.5°C)	Methanol (at 67.5°C)
Specific heat (kJ/kg.°C)	4.2	2.84
Thermal conductivity (W/m.°C)	0.59	0.19
Density (kg/m^3)	995	750
Viscosity (cP)	0.8	0.34

The following heat exchanger configuration is available:

- Fixed tube sheet shell and tube exchanger: 1 shell pass and 2 tube passes.
- Brackish water on the tube side and methanol on the shell side.
- 918 number of cupro-nickel tubes of 20 mm OD, 16 mm ID, 4.88 m long each, arranged in triangular pitch, pitch of 1.25 times OD.
- Shell diameter: ID 894 mm, baffle spacing: 356 mm; 25% cut segmental baffles
- Tube side nozzle flanges: 100 NB, 150 psi, Shell side nozzle flanges: 150 NB, 150 psi

(a) Make suitable calculations, to show that the above design is satisfactory. (Start with an approx value for U of 600 W/m^2.°C).

(b) Draw to scale the half-sectional elevation and tube-sheet layout of the heat exchanger. Mark the salient parts of the exchanger.

Design Calculations:

Coolant is corrosive, so assign to tube-side.

$$\text{Heat capacity methanol} = 2.84 \text{ kJ/kg}^\circ\text{C}$$

$$\text{Heat load} = \frac{100{,}000}{3600} \times 2.84(95 - 40) = 4340 \text{ kW}$$

$$\text{Heat capacity water} = 4.2 \text{ kJ/kg}^\circ\text{C}$$

$$\text{Cooling water flow} = \frac{4340}{4.2(40 - 25)} = 68.9 \text{ kg/s}$$

$$\Delta T_{\text{lm}} = \frac{(95 - 40) - (40 - 25)}{\ln \dfrac{(95 - 40)}{(40 - 25)}} = 31^\circ\text{C}$$

Use one shell pass and two tube passes

$$R = \frac{95 - 40}{40 - 25} = 3.67$$

$$S = \frac{40 - 25}{95 - 25} = 0.21$$

From Figure 12.19

$$F_t = 0.85$$

$$\Delta T_m = 0.85 \times 31 = 26^\circ\text{C}$$

From Figure 12.1

$$U = 600 \text{ W/m}^2\,^\circ\text{C}$$

Provisional area

$$A = \frac{4340 \times 10^3}{26 \times 600} = 278 \text{ m}^2$$

Choose 20 mm o.d., 16 mm i.d., 4.88-m-long tubes $\left(\frac{3}{4}\text{in.} \times 16 \text{ ft}\right)$, cupro-nickel. Allowing for tube-sheet thickness, take

$$L = 4.83 \text{ m}$$

$$\text{Area of one tube} = 4.83 \times 20 \times 10^{-3}\pi = 0.303 \text{ m}^2$$

$$\text{Number of tubes} = \frac{278}{0.303} = \underline{\underline{918}}$$

As the shell-side fluid is relatively clean use 1.25 triangular pitch.

$$\text{Bundle diameter } D_b = 20\left(\frac{918}{0.249}\right)^{1/2.207} = 826 \text{ mm}$$

Use a split-ring floating head type.

From Figure 12.10, bundle diametrical clearance = 68 mm,

$$\text{shell diameter, } D_s = 826 + 68 = 894 \text{ mm.}$$

Tube Side Heat Transfer Coefficient

$$\text{Mean water temperature} = \frac{40+25}{2} = 33°\text{C}$$

$$\text{Tube cross-sectional area} = \frac{\pi}{4} \times 16^2 = 201\ \text{mm}^2$$

$$\text{Tubes per pass} = \frac{918}{2} = 459$$

$$\text{Total flow area} = 459 \times 201 \times 10^{-6} = 0.092\ \text{m}^2$$

$$\text{Water mass velocity} = \frac{68.9}{0.092} = 749\ \text{kg/s m}^2$$

$$\text{Density water} = 995\ \text{kg/m}^3$$

$$\text{Water linear velocity} = \frac{749}{995} = 0.75\ \text{m/s}$$

$$\frac{h_i d_i}{k_f} = j_h Re Pr^{0.33}\left(\frac{\mu}{\mu_w}\right)^{0.14}$$

$$\text{Viscosity of water} = 0.8\ \text{mNs/m}^2$$

$$\text{Thermal conductivity} = 0.59\ \text{W/m°C}$$

$$Re = \frac{\rho u d_i}{\mu} = \frac{995 \times 0.75 \times 16 \times 10^{-3}}{0.8 \times 10^{-3}} = 14{,}925$$

$$Pr = \frac{C_p \mu}{k_f} = \frac{4.2 \times 10^3 \times 0.8 \times 10^{-3}}{0.59} = 5.7$$

$$\text{Neglect}\left(\frac{\mu}{\mu_w}\right)$$

$$\frac{L}{d_i} = \frac{4.83 \times 10^3}{16} = 302$$

From Figure 12.23, $j_h = 3.9 \times 10^{-3}$

$$h_i = \frac{0.59}{16 \times 10^{-3}} \times 3.9 \times 10^{-3} \times 14{,}925 \times 5.7^{0.33} = 3812\ \text{W/m}^2\,°\text{C}$$

Shell Side Heat Transfer Coefficient:

$$A_s = \frac{(p_t - d_o)D_s l_B}{p_t}$$

$$G_s = \frac{W_s}{A_s}$$ where W_s = fluid flow-rate on the shell-side, kg/s,

$$u_s = \frac{G_s}{\rho}$$ ρ = shell-side fluid density, kg/m^3.

For an equilateral triangular pitch arrangement:

$$d_e = \frac{4\left(\frac{p_t}{2} \times 0.87 p_t - \frac{1}{2}\pi \frac{d_o^2}{4}\right)}{\frac{\pi d_o}{2}} = \frac{1.10}{d_o}(p_t^2 - 0.917 d_o^2)$$

where d_e = equivalent diameter, m.

$$Re = \frac{G_s d_e}{\mu} = \frac{u_s d_e \rho}{\mu}$$

$$\text{Choose baffle spacing} = \frac{D_s}{5} = \frac{894}{5} = 178 \text{ mm.}$$

$$\text{Tube pitch} = 1.25 \times 20 = 25 \text{ mm}$$

$$\text{Cross-flow area } A_s = \frac{(25 - 20)}{25} 894 \times 178 \times 10^{-6} = 0.032 \text{ m}^2$$

$$\text{Mass velocity, } G_S = \frac{100{,}000}{3600} \times \frac{1}{0.032} = 868 \text{ kg/s m}^2$$

$$\text{Equivalent diameter } d_e = \frac{1.1}{20}(25^2 - 0.917 \times 20^2) = 14.4 \text{ mm}$$

$$\text{Mean shell side temperature} = \frac{95 + 40}{2} = 68^\circ\text{C}$$

Methanol density = 750 kg/m^3

Viscosity = 0.34 mNs/m^2

Heat capacity = 2.84 kJ/kg°C

Thermal conductivity = 0.19 W/m°C

$$Re = \frac{G_s d_e}{\mu} = \frac{868 \times 14.4 \times 10^{-3}}{0.34 \times 10^{-3}} = 36{,}762$$

$$Pr = \frac{C_p \mu}{k_f} = \frac{2.84 \times 10^3 \times 0.34 \times 10^{-3}}{0.19} = 5.1$$

Choose 25 per cent baffle cut, from Figure 12.29

$$j_h = 3.3 \times 10^{-3}$$

Without the viscosity correction term

$$h_s = \frac{0.19}{14.4 \times 10^{-3}} \times 3.3 \times 10^{-3} \times 36{,}762 \times 5.1^{1/3} = 2740 \text{ W/m}^2\,{}^\circ\text{C}$$

Overall Heat Transfer Coefficient:

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln\left(\frac{d_o}{d_i}\right)}{2k_w} + \frac{d_o}{d_i} \times \frac{1}{h_{id}} + \frac{d_o}{d_i} \times \frac{1}{h_i}$$

where U_o = the overall coefficient based on the outside area of the tube, W/m$^2\,{}^\circ$C,
h_o = outside fluid film coefficient, W/m$^2\,{}^\circ$C,
h_i = inside fluid film coefficient, W/m$^2\,{}^\circ$C,
h_{od} = outside dirt coefficient (fouling factor), W/m$^2\,{}^\circ$C,
h_{id} = inside dirt coefficient, W/m$^2\,{}^\circ$C,
k_w = thermal conductivity of the tube wall material, W/m°C,
d_i = tube inside diameter, m,
d_o = tube outside diameter, m.

$$\frac{1}{U_o} = \frac{1}{2740} + \frac{1}{5000} + \frac{20 \times 10^{-3} \ln\left(\frac{20}{16}\right)}{2 \times 50} + \frac{20}{16} \times \frac{1}{3000} + \frac{20}{16} \times \frac{1}{3812}$$

$$U_o = \underline{\underline{738 \text{ W/m}^2\,{}^\circ\text{C}}}$$

which is well above the assumed value of 600 W/m^2.$^\circ$C. Hence the given configuration is satisfactory.

Pressure Drop Calculations:

Tube-side

From Figure 12.24, for $Re = 14{,}925$

$$j_f = 4.3 \times 10^{-3}$$

Neglecting the viscosity correction term

$$\Delta P_t = 2\left(8 \times 4.3 \times 10^{-3}\left(\frac{4.83 \times 10^3}{16}\right) + 2.5\right)\frac{995 \times 0.75^2}{2}$$

$$= 7211 \text{ N/m}^2 = 7.2 \text{ kPa (1.1 psi)}$$

low, could consider increasing the number of tube passes.

Shell side

$$\text{Linear velocity} = \frac{G_s}{\rho} = \frac{868}{750} = 1.16 \text{ m/s}$$

From Figure 12.30, at Re = 36,762

$$j_f = 4 \times 10^{-2}$$

Neglect viscosity correction

$$\Delta P_s = 8 \times 4 \times 10^{-2} \left(\frac{894}{14.4}\right) \left(\frac{4.83 \times 10^3}{178}\right) \frac{750 \times 1.16^2}{2}$$

$$= 272{,}019 \text{ N/m}^2$$

$$= 272 \text{ kPa (39 psi) too high,}$$

could be reduced by increasing the baffle pitch. Doubling the pitch halves the shell-side velocity, which reduces the pressure drop by a factor of approximately $(1/2)^2$

$$\Delta P_s = \frac{272}{4} = 68 \text{ kPa (10 psi), acceptable}$$

This will reduce the shell-side heat-transfer coefficient by a factor of $(1/2)^{0.8}$($h_o \propto Re^{0.8} \propto u_s^{0.8}$)

$$h_o = 2740 \times (\tfrac{1}{2})^{0.8} = 1573 \text{ W/m}^2\,{}^\circ\text{C}$$

This gives an overall coefficient of 615 W/m$^2\,{}^\circ$C – still above assumed value of 600 W/m$^2\,{}^\circ$C.